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Silicon Nitride – An Overview

Chemical Formula

Si_3N_4

Topics Covered

Background

Silicon nitride (Si_3N_4) was developed in the 1960s and '70s in a search for fully dense, high strength and high toughness materials. A prime driver for its development was to replace metals with ceramics in advanced turbine and reciprocating engines to give higher operating temperatures and efficiencies. Although the ultimate goal of a ceramic engine has never been achieved, silicon nitride has been used in a number of industrial applications, such as engine components, bearings and cutting tools.

Silicon nitride has better high temperature capabilities than most metals combining retention of high strength and creep resistance with oxidation resistance. In addition, its low thermal expansion coefficient gives good thermal shock resistance compared with most ceramic materials.

View properties

Key suppliers
Dynamic-Ceramic Ltd
International Ceramic Engineering

Key services
CERAM Research

Key experts
Chris Sorrell
Simeon (Sim) Parrott
John Cotton

Production

Pure silicon nitride is difficult to produce as a fully dense material. This covalently bonded material does not readily sinter and cannot be heated over 1850^{o}C as it dissociates into silicon and nitrogen. Dense silicon nitride can only be made using methods that give bonding through indirect methods, such as small chemical additions to aid densification. These chemicals are known as sintering aids, which commonly induce a degree of liquid phase sintering.

Types of Silicon Nitride

Since the material properties strongly depend on the fabrication method, silicon nitride cannot be considered as a single material. The three main types of silicon nitride are:

- Reaction bonded silicon nitride (RBSN)
- Hot pressed silicon nitride (HPSN)
- Sintered silicon nitrides (SSN)

Reaction bonded silicon nitride is made by direct nitridation of a compacted silicon powder, and because of the difficulty of ensuring complete reaction, it is hard to achieve a high component density. Usual densities are in the range 2300 - 2700kg.m^{-3} compared with 3200kg.m^{-3} for hot pressed and sintered silicon nitride. The higher density gives the HPSN and SSN materials better physical properties and means they are used in more demanding applications. The nitridation produces only a small volume change, which means that RBSN components do not need to be machined after fabrication and complex near net shapes can be produced in a single process stage.

Key Properties

Applications exploit the following properties of silicon nitride:

- low density

- high temperature strength
- superior thermal shock resistance
- excellent wear resistance
- good fracture toughness
- mechanical fatigue and creep resistance
- good oxidation resistance

Applications

The material is used currently in niche market applications for example in reciprocating engine components and turbochargers, bearings, metal cutting and shaping tools and hot metal handling.

Reciprocating Engine Components

The largest market for silicon nitride components is in reciprocating (diesel and spark ignited) engines for combustion components and wear parts. Their development has been a more difficult and complex task than envisaged. Cost factors and the severe technological problems of mass producing complex ceramic components have limited growth, but the material has also met with design conservatism and concerns about the reliability of ceramic components.

Small dense sintered silicon nitride components are used in both automobile and truck engines for applications where stresses and temperatures are relatively low and the consequence of failure is not catastrophic. Examples of components include:

Diesel engines

- glow plugs for faster start-up
- precombustion chambers (swirl chambers) for lower emissions, faster start-up and lower noise
- turbocharger (approx. 10 cm dia.) for reduced engine lag and emissions

Spark ignited engines

- rocker arm pads for lower wear
- turbocharger (approx. 5cm dia) for lower inertia and less engine lag
- exhaust gas control valve for increased acceleration.

Most of these components are manufactured in Japan and the United States. As examples of production levels, there is an estimated 300,000 sintered silicon nitride turbochargers made annually. In the US, emission reduction has driven ceramic component development and components are used predominantly in medium and heavy duty engines. In Japan, improved performance has been the main driver and the components are used in light duty engines.

Development work is now concentrating on the cautious introduction of further components in applications where low mass or increased wear resistance are needed, for example as exhaust valves and valve springs.

Bearings

The wear resistance, low friction and high stiffness of fully dense silicon nitride improve the performance of high temperature unlubricated roller and ball bearings. HPSN bearings have shown increased bearing life, better speed capability and greater corrosion resistance compared to conventional higher-density steel and hard metal bearings.

The vast majority of silicon nitride bearings are used in hybrid ball bearings (bearings with ceramic balls and steel races). Applications include machine tool spindles, vacuum pumps and sterilisable and unlubricated dental drills.

All ceramic bearings are used in applications where corrosion, electric or magnetic fields prohibit the use of metals. For example in tidal flow meters where seawater attack is a problem or electric field seekers.

Although concerns over reliability no longer limit the application of silicon nitride in bearings, their cost must be reduced before wider application is seen.

Metal Working

Hot hardness, fracture toughness and thermal shock resistance mean that sintered silicon nitride can cut cast iron, hard steel and nickel based alloys with surface speeds up to 25 quicker than those obtained with conventional materials such as tungsten carbide.

Silicon nitride based cutting tools are now used in considerable numbers to machine cast iron by the automotive industry and nickel superalloys by the aero industries. The current market value for silicon nitride cutting tools is about $50 million per year, however, since it is not suited to machining high silicon aluminium alloys, its future growth will slow as the automotive industry make wider use of aluminium rather than cast iron blocks.

Industrial Applications

There is a range of general industrial applications where the material properties can be exploited. Reaction bonded silicon nitride (RBSN) is often used in these cases as the operating conditions are less demanding than in the preceding applications.

Applications include:

- Non automotive wear components are a growing market for silicon nitride. For example, fixtures to position and transfer metal parts during processes such as induction heating and resistance welding exploit the electrical insulation, wear resistance, low thermal conductivity and thermal shock resistance of the material.
- Spouts, nozzles, thermocouple sheaths and melting crucibles for handling molten aluminium, zinc, tin and lead alloys. The increasing requirement for controlled metal purity makes the use of metallic components less desirable.
- Arc welding nozzles are also a steady market for RBSN given the strength, electrical resistance and thermal shock resistance of the material
- Specialised kiln furniture with low thermal mass and high thermal shock resistance for use in firing components such as dental porcelain where repeated thermal cycling is required.

Future Applications

Significant growth in use is needed if silicon nitride is to move from a niche to a major industrial material. This move requires a decreased cost coupled with improved or at least maintained properties and reliability. Engine technology is the area likely to benefit most from future growth as reduced fuel consumption and reduced emission become ever stronger drivers. Paradoxically, the material has yet to be widely used in gas turbine engines (the original reason for the material's development), mainly because small to medium sized turbine engines have yet to find wide application.

Source: Ceram Research Ltd

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